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Determination opposition of Jupiter from VLBI observations of Ulysses

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Very-Long Baseline Interferometry (VLBI) observations of the Ulysses spacecraft near its encounter with Jupiter on February 8, 1992, were made to determine the position of Jupiter with respect to well known extragalactic radio sources. Spacecraft range and Doppler data were used to determine the position of the spacecraft with respect to Jupiter. Thirty four VLBI observations of the spacecraft were made within 30 days of Ulysses' closest approach to Jupiter, using the California-Spain and California-Madrid baselines of NASA's Deep Space Network. When combined, these data determine the position of Jupiter at the time of encounter with an accuracy of 0.003" in right ascension and 0.005" in declination. In addition, the Earth-Jupiter distance was determined to 50 m. This position determination can be used to greatly improve the ephemeris of Jupiter.

INTRODUCTION

The Ulysses mission is a cooperative project of NASA and the European Space Agency. The Ulysses spacecraft is a science probe designed to measure charged and neutral particles, magnetic fields, electromagnetic waves, and ultraviolet and X-ray emissions at high solar latitudes. To achieve an orbit highly inclined to the ecliptic plane, Ulysses made a close approach to Jupiter in February 8, 1992.

Two-way range and two-way Doppler measurements were made between Ulysses and tracking stations from NASA's Deep Space Network (DSN) to enable orbit determination to support mission operations. In addition, measurements of Ulysses were made using a Very-Lcmg Baseline Interferometry (VLBI) technique which measured the angular separation of the spacecraft relative to a reference extra galactic radio source (Border at al., 1982). The VLBI measurements were made to improve the orbit determination of Ulysses and allow for an improved position determination of Jupiter that could be used to improve the ephemeris of Jupiter prior to the Galileo spacecraft arrival at Jupiter, which will occur December 7, 199S.

VLBI observations determine the relative positions of extragalactic radio sources to about 1 mas (0.001") accuracy (Sovers at al., 1988; Ma et al., 1990). Beginning in 1988 the international Earth Rotation Service (IERS) was formed to facilitate reporting Earth orientation in a standard way. The IERS adopted a conventional celestial reference frame defined by the positions of extragalactic radio sources (Arias et al., 1988). An independent reference frame has been used to reduce Lunar Laser Ranging (LLR), ranging to the Viking landers, and radar ranging data to Mercury and Venus to define an inertial reference frame for the ephemerides of the inner planets (Standish and Williams, 1990). Comparison of Earth orientation determined by LLR with respect to the Earth-Moon orbit and by VLBI with respect to the extragalactic radio sources has been performed to determine the ephemerides of the inner planets with respect to the IERS celestial reference frame with an accuracy of about 3 mas (Folkner et al. 1994).

The ephemerides of the outer planets has been heavily dependent on optical measurements due to a scarcity of more accurate measurements. in consequence the ephemeris accuracies of the outer planets are much poorer that those of the inner planets (Standish, 1990). The Very Large Array in Socorro, New Mexico was used to observe

Callisto and Ganymede and infer the position of Jupiter with respect to extragalactic radio sources in April, 1983 (Muhleman et al., 1985) with an accuracy of 0.025". With no other observations of Jupiter with respect to extragalactic radio sources, VLBI observations of the Ulysses spacecraft near its encounter with Jupiter can be used to greatly improve the accuracy of the Jupiter ephemeris.

VLBI OBSERVATIONS

The Ulysses spacecraft is spin stabilized and communicates through a high-gain antenna with its boresight on the spin axis. The primary spacecraft radio system is an S-band (2.1 GHz) uplink (from Earth tracking stations to the spacecraft) and X-band (8.4 GHz) downlink from the spacecraft. The radio system is used for radio metric measurements as well as for scientific and engineering telemetry. Two-way Doppler data are acquired when the spacecraft transmits a radio signal that is a coherent multiple of the uplink signal; comparison of the transmitted and received signal frequencies at the Earth tracking station gives a measure of the spacecraft velocity along the line of sight to Earth. Two-way range data are acquired when the tracking station transmits a 2-MHz square-wave modulation on the carrier that is transponder by the spacecraft. Measurement of the group delay between transmission and reception of the 'ranging code' gives a measure of the Earth-spacecraft range. Solar plasma limits the Doppler accuracy to about 1 mm/s and causes a variation in the observed Earth-spacecraft range of about 2 m, with an uncalibrated bias of about 30 m. The gravitational acceleration experienced by the spacecraft near a planetary body induces signatures in the Doppler and range data that enable the determination of the position of the spacecraft with respect to the body.

Spacecraft VLBI observations, which measure the plane-of-sky angular separation between a spacecraft and extragalactic radio source (quasar), have been performed since the encounters of the Voyager spacecraft with Saturn (Border et al., 1982). Angular position is inferred by measuring the difference in arrival time (delay) of a radio signal at two tracking stations separated by inter-continental distances. The angle is measured along a direction parallel to the projection of the baseline vector (between the two tracking stations) on the plane of the sky. By combining VLBI measurements along two non-parallel baselines, both components of the spacecraft angular position can be determined.

The arrival time of the spacecraft signal at each antenna is measured by tracking the phase of the radio wavefront relative to the station's atomic clock standard. If only the carrier frequency (S or X-band) of the signal is tracked, the arrival times will be biased by an unknown number of integer cycle periods. Unambiguous delay measurements between widely separated antennas typically require that the spacecraft signal consist of two or more tones that span a bandwidth of several MHz. The phase of beat frequencies between pairs of tones in the signal can then be used to measure the time of arrival. *A priori* spacecraft position estimates from fitting Doppler and range data are usually accurate enough to resolve the integer cycle ambiguity for the beat frequency.

The spacecraft VLBI measurement is always performed immediately before or after a VLBI measurement for an angularly nearby quasar with known position. This allows accurate relative determination of the spacecraft's angular position. Systematic errors arising from uncalibrated delays in the station instrumentation, Earth media, solar plasma and errors from the station clocks are largely common to both spacecraft and quasar measurements. The angular accuracy of the spacecraft position is given by the ratio of the arrival time accuracy to length of the projected baseline. For Ulysses, VLBI observations were made primarily by using tones produced as harmonics of telemetry modulation frequencies of 65.5 and 131 kHz. Harmonics with sufficient power to be detected at the stations spanned a bandwidth of 5-6 MHz, and the delay accuracy was about 1.5 ns.

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The DSN baselines employed for Ulysses VLBI measurements were between Goldstone, California and Madrid, Spain, and between Goldstone and Canberra, Australia. For the sixty-day period centered about time of closest approach to Jupiter, a total of 34 VLBI observations were made. The average baseline length between the DSN complexes is ~8000 km, so the 1.5-ns delay accuracy corresponds to an angular accuracy of about ~0.012" for each measurement. The majority of the measurements were made with respect to the source P 1055+01, which is a primary source in the IERS celestial reference frame.

SOLUTION METHOD

The Doppler, range, and VLBI data were used to estimate the spacecraft trajectory parameters and the position of Jupiter at the time of encounter. The orbit determination process used is similar to that used for the operational spacecraft navigation (McElrath et al., 1992). The data employed spanned 60 days centered about the time of closest approach to Jupiter, which occurred on February 8, 1992. Range and Doppler data were acquired almost continuously throughout the data arc.

The spacecraft trajectory was integrated from initial position and velocity conditions using models for the dynamic forces on the spacecraft. The modeled gravitational forces on the spacecraft were due to the masses of the Sun, Jupiter, the Galilean satellites, and the oblateness of Jupiter. The gravity model for the Jovian system is described by Campbell and Synnott (1985). Like most spinning spacecraft, Ulysses has a relatively low level of non-gravitational accelerations acting on the spacecraft. Solar radiation pressure, which is low at Jupiter, was modeled as a stochastic process with 20% uncertainty. Attitude control maneuvers, which occurred about every three days with a resulting velocity change almost entirely in the Earth-spacecraft direction, were estimated.

Radio source positions were adopted from the IERS radio frame (IERS 1993). The planetary ephemeris DE200 (Standish, 1982) was rotated to orient the orbit of the Earth properly in IERS radio frame (Folkner et al., 1994). Locations for the stations of the DSN were consistent with the IERS terrestrial reference frame. The station locations were mapped from Earth-fixed locations to inertial space using models for precession, nutation, solid Earth tides, and calibrations for polar motion and length-of-day variations as given by the IERS (IERS, 1993). Computed values for measurements were derived from nominal values for the spacecraft epoch state, force models, and inertial station locations, and calibration for propagation delays due to Earth ionosphere (Mannucci et al., 1993) and troposphere (Chao, 1974). A least-squares fit to the observed minus computed measurements was made to estimate model parameters.

The estimated parameters included the spacecraft epoch state, corrections to the orbital elements of Jupiter, a constant scaling parameter for the solar radiation pressure model, and the magnitudes of the velocity impulses caused by attitude control maneuvers. Time variation in the solar radiation pressure was estimated as a Markov process with a 30-day time constant. The spacecraft spin rate, detectable in the Doppler data, was estimated as a Markov process with a 15-day time constant. Finally a range calibration bias was estimated for each tracking pass.

RESULTS

Tables 1 and 2 give the estimated position of Jupiter, at a time near the closest approach of the Ulysses spacecraft, in Cartesian and spherical coordinates. To avoid complications of light-time calculation, time transformations, and other effects, Tables 1 and 2 give the instantaneous Earth-Jupiter vector in the IERS celestial reference frame. That is, the Earth-Jupiter vector is the difference between the position of the Jupiter system barycenter at the specified solar-system barycentric coordinate time (TDB) and the position of the center of the Earth at the same coordinate time. For reference, the Earth-Jupiter vector is also given in the widely available ephemeris DE200 (Standish 1982).

The uncertainties in Table 2 are expected to reflect the actual uncertainties as realistically as possible. The right ascension and declination estimated for Jupiter are more accurate than any other measurements. The Ulysses position determination will make a significant contribution to determining the ephemeris of Jupiter prior to Galileo's encounter in December 1995.

Table 1. Cartesian coordinates of Jupiter with respect to Earth on 8-Feb-1992 12:00:00.000 TDB

	Estimated position	Position in DE200
x(km)	-638101675,66	-638101829.84
y(km)	180208450.78	180208102.37
z(km)	95074290.31	95073865.82

Table 2. Spherical coordinates of Jupiter with respect to Earth on 8-Feb-1992 12:00:00.000 TDB

	Estimated position	Position in DE200
range (km)	669841738 .69±.01	669841731.58
right ascension	$10^h\ 56^m\ 55.1065^s \pm 0.0002^s$	$10^h\ 56^m\ 55.1143^s$
declination	8°9' 35.489"±0.005"	8°9'6.357"

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